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Novel Post-Combustion Capture Technologies on a Lignite Fired Power Plant - Results of the CO2CRC/H3 Capture Project

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Abstract

Commissioned in 2009, the CO2CRC/H3 Capture Project is demonstrating post-combustion carbon capture (PCC) on a lignite fired power plant in the Latrobe Valley, Victoria, Australia. The facility is located within International Power's Hazelwood Power Plant and uses three different CO_2 capture technologies - solvent, adsorption and membrane processes. This project, addressing the PCC issues specific for Victorian brown coal fired power stations, was initiated in July 2007 as a three year research project by the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) under the Victorian State Government's Energy Technology Innovation Strategy (ETIS) program. The project is part of the Latrobe Valley Post Combustion Capture (LVPCC) Project – a multi site, multi scale, multi technology PCC trial. The integrated research and development program includes an evaluation of these technologies for commercial scale application. This paper describes the technologies used, how they have progressed from laboratory to pilot demonstration, the main outcomes, and plans for future developments.

Keywords: PCC, Post-combustion Carbon Capture technologies, solvent, adsorbent & membrane capture technologies; CCS

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1. Introduction

Brown coal, the cheapest source of fossil-based energy, is the major fuel for power plants in the state of Victoria, which has an estimated brown coal reserve of over 500 years. However, the high level of CO_2 emissions associated with this fuel makes it a significant target for reducing greenhouse gases. This led the Victorian State Government to initiate a program under their ETIS Program to address CO_2 reductions while maintaining sustainable economic advantages. Partly funded by this ETIS initiative, CO2CRC commenced a three year research program in post-combustion capture in June 2007, based at International Power's Hazelwood Power Plant in the Victorian Latrobe Valley. CO2CRC is uniquely placed to deliver a comprehensive program, as it includes research partners from a range of universities and is supported by a large number of industrial and government organizations. The post-combustion project specifically involves researchers from the University of Melbourne, Monash University and the University of New South Wales, in addition to Process Group, a leading provider of carbon capture process plants, and the power plant owner, International Power.

The CO2CRC/H3 post-combustion demonstration project is associated with a 25 tonne per day CO_2 capture plant at International Power's Hazelwood power plant in Victoria. This plant was designed and supplied by Process Group under contract to International Power and made available to the CO2CRC under the H3 Capture Project.In post-combustion capture, the flue gas is essentially at atmospheric pressure and contains N_2, CO_2, O_2 and H_2O, as well as particulate matter and SOx and NOx. The CO_2 makes up about 11-12 per cent of the flue gas.

The trials are focussed not only on the existing commercial separation techniques (solvent absorption with amino acid and potassium carbonate solvents) [1] [2], but is also used to test novel capture options; specifically membrane and adsorption [3] [4] [5]; for post-combustion CO_2 capture. The program includes the evaluation of the performance of membrane module configurations under real flue gas conditions and the monitoring of the effects of minor gas components in the feed gases; and the assessment of the adsorption process, equipment and different adsorbents under various working conditions and equipment configurations [4].

The ultimate aim of the project is to resolve key issues for all technologies (technical risk and cost reduction) and to extract the maximum information on materials cost and properties; process selection; impurity effects and their remedy; energy integration; process modelling & simulation; equipment design and economics of commercial application. The project will help to identify the most effective commercial technology for a retrofit or a new capture plant.

Each of these technologies is discussed in more details below. Heat integration aspects will be presented separately in the poster no 173 of GHGT-10; while more details are also provided on membrane technology in two papers [6, 7] and on adsorption in poster no 707 of GHGT-10 and a conference presentation [8].

Solvent Absorption

1.1. Background

The International Power/Process Group solvent capture plant is the largest post-combustion capture plant on a power plant in Australia and has been designed to initially capture 25 tpd (expandable up to 50 tpd) of CO_2 from flue gas using a commercial amino acid based solvent (BASF PuratTreat-F^{TM}). This trial, known as International Power's CO_2 Capture Project, had been successfully capturing CO_2 since the plant was commissioned in July 2009 providing operational experience to the power plant personnel as well as allowing the use of CO_2 for reducing the pH of the plant's ash water. In a separate trial, known as the CO2CRC/IPT H3 project, a promoted potassium carbonate based solvent is being investigated since May 2010.

1.2. Process Description

In order to endure the use of the plant for subsequent solvent research Process group designed the Hazelwood capture plant with multi-solvent capability. That is the plant designed for use with a range of capture solvents. A process flow diagram of the solvent pilot plant for post-combustion capture is presented in Figure 1. Feed gas enters the solvent plant through the Scrubber/Direct Contact Cooler (DCC), which cools the gas from around 200^{o}C to 40^{o}C prior to entering the Absorber. The DCC is also fitted with a spray section to remove the entrained ash particles within the flue gas. Flue gas exiting the DCC then passes to the Flue Gas Blower, where it is compressed to 10 kPag. The gas then passes to the Absorber, where it rises through two sections of Nutter rings and is brought into contact with a solution of lean solvent. As the gas rises through the column, the CO_2 level is progressively reduced. Rich solvent drains into the sump of the Absorber. Rich Solvent is then pumped to the Lean/Rich Exchanger by the Rich Solvent Pump that preheats the solvent to 117^{O}C prior to entering the Regenerator, which also contains Nutter rings random packing. Heat for regeneration is provided via a steam-heated Reboiler. Lean solvent from the Reboiler is then pumped by the Lean Solvent Pumps before being cooled by the Lean/Rich Exchanger. The lean solvent then passes through the Lean Solvent Cooler (water cooled) to reduce its temperature to 40^{o}C before returning to the Absorber. At the vapour exit of the Regenerator CO_2 removed from the solvent passes through the Overheads Condenser (water cooled) to condense as much of the associated water vapour as possible. The fluid then passes through two liquid ring compressors to compress the gas to 120 kPag and then 400 kPag. Water is removed from the gas stream after each compressor via the Reflux Accumulator and Liquid Separator vessels respectively. In order to maintain solvent efficiency, antifoam and chemical reagents, namely KOH, are added from separate automated dosing tanks.

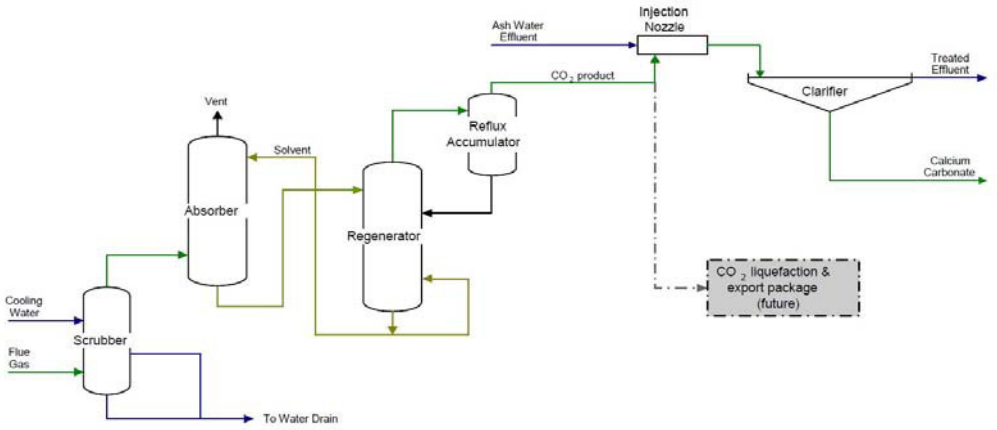

Figure 1: Process flow diagram of Hazelwood post combustion CO_2 capture solvent plant (Hooper, 2008) [4]

1.3. Pilot Plant Performance

The solvent capture plant has been in steady state operation using BASF PuraTreat-F^{TM} for more than 1800 hours between July 2009 and April 2010. During this time the capture planted has been able to capture 20-25 tonnes per day of CO_2 with 80-90% recovery (Figure 2). Numerous shutdowns occurred during this period to complete plant maintenance, besides fluctuation in the steam supply, poor performance of heat exchanger and instrumentation errors were recorded. However, learning process in handling operational issues was significant and the plant was able to produce numerous valuable data. The thermal energy consumption (Figure 3) appeared to be higher than expected, the reasons of which are under investigation. During this trial samples were also taken to assess how flue gas components such as SO_x interact with the solvent. It was found that most SO_x was removed in the direct contact cooler (resulting in cooling water with a low pH). However the sulphur concentration in the solvent was also observed to increase by up to 5-6 times the initial concentration during the trial period (approximately 8 months).

This accumulation of sulphur could become an issue for solvent performance and is the subject of further investigation.

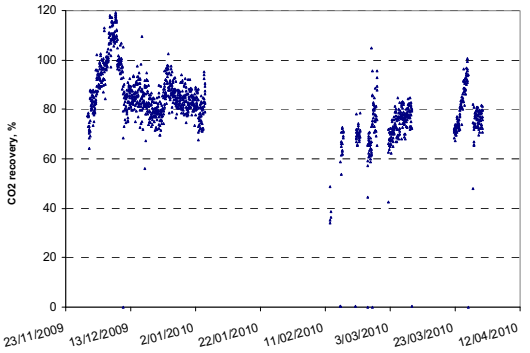

Figure 2: % CO_2 recovery using BASF PuraTreat-F^{TM} solvent

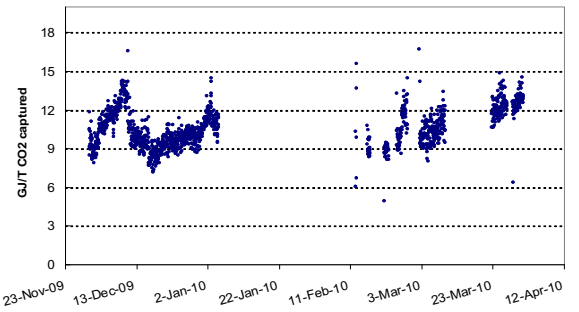

Figure 3: Energy consumption using BASF PuraTreat-F^{TM} solvent

1.4. Future Directions

The CO2CRC/H3 Capture project aims to test the CO_2 absorption performance of potassium carbonate (K_2CO_3) solvent. A 30wt% unpromoted K_2CO_3 solution is currently being used to capture CO_2 and will be followed by a trial with a promoted potassium carbonate solution. Potassium carbonate is a promising solvent for capturing CO_2 when compared to other commercially available solvents as it is relatively cheap, less toxic and less prone to solvent degradation which is commonly seen with amine solvents at high temperatures and in the presence of oxygen. Potassium carbonate can be operated at high temperatures which will improve thermal efficiency and has the ability to remove CO_2 as well as other polluting gases such as SO_x and NO_x which is an important feature at Australian coal fired power stations which currently do not remove these species with desulfurization processes.

The overall aims of this project are as follows:

- trial a number of solvents including a hot potassium carbonate-promoted solvent;
- reduce the energy consumption for solvent regeneration;
- assess the energy integration options for the power plant and capture processes;
- control or avoid solvent degradation and corrosion;
- understand the interaction between the solvent system and impurities present in the flue gas, including SO_x and NO_x; and
- review the technical and economic issues for commercial use of post combustion capture in existing and new Victorian brown coal power stations.

2. Adsorption

2.1. Background and Process Description

The adsorption plant is a 3 bed, ~1 TPD multiple-layered vacuum swing adsorption process and allows us to investigate the performance of commercial and novel adsorbents to separate CO_2 from flue gas with high humidity levels, as well as exploring their tolerance to impurities such as SOx, NOx. The plant comprises three adsorption columns, a feed gas booster, a recycle compressor, a vacuum pump package, a heat exchanger, manifolds etc. Multiple layered adsorbents are used: water-selective adsorbents are used to remove the water in the flue gas and acidic gas resistant adsorbents are also utilized to remove SOx/NOx. Secondary adsorbents are CO_2-selective to adsorb CO_2 in the adsorption step and release CO_2 in the desorption step in a cyclic manner. The flue gas (~200°C) coming from the power station stack blower is sent through a direct contact cooler (DCC) and cooled down to ~40°C. This cooled flue gas (10-15% CO_2, saturated with water vapour, N_2, O_2, and other ppm level impurities) then goes through a feed gas booster to be compressed to ~150kPa.a and is cooled by heat exchange before entering the column. In the feed/adsorption step, CO_2 is selectively adsorbed onto the adsorbents with CO_2-lean gas leaving the column top and sent to the stack. After additional bed to bed

interaction steps, the beds are evacuated by a vacuum pump pack to around 1kPa.a in the desorption step and CO_2-rich product gas (110kPa.a) is ready for compressing and sequestration, though in this specific project this product gas stream is sent back to the inlet of the general feed gas blower. The adsorption and desorption are operated in a cyclic manner and the whole process is automatically controlled by Allen-Bradley PLC with real-time data acquisition. The heat exchanger is available to permit studies of feed temperature effects on the process behaviour. Other process parameters, such as cycle time, adsorption pressure, desorption pressure, were investigated. Issues related to construction, commissioning and operation will be discussed as well as preliminary data on system performance.

2.2. Pilot Plant Performance

After commissioning of the adsorption rig, a simple 6-step cycle was used to run the process as shown in Figure 4.

Figure 4: 6-step simple cycle without purge

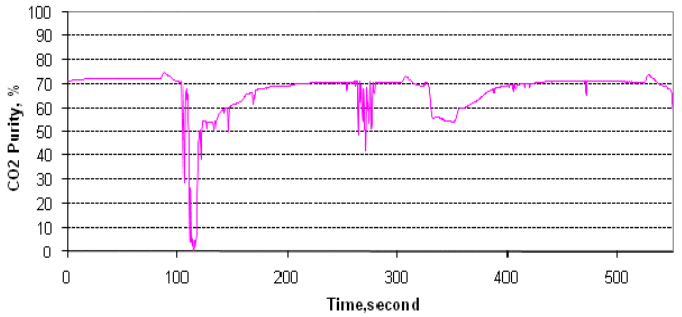

Figure 5: CO2 purity over time

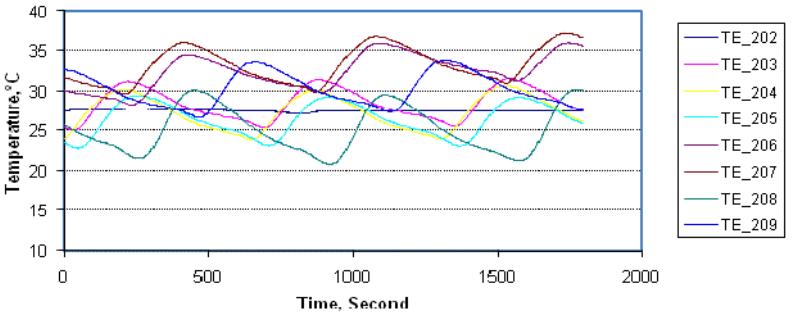

Figure 6: Temperature swing profiles within adsorption column

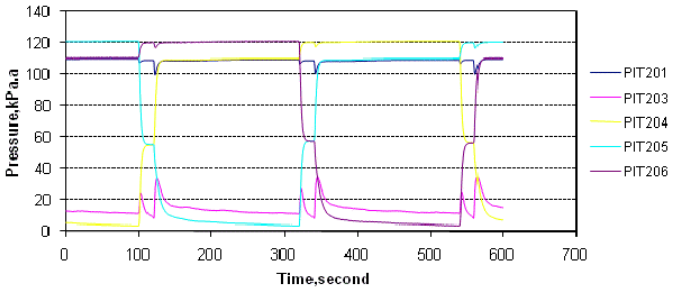

Figure 7: Pressure profiles within the adsorption column

The reason for starting the process with a simple cycle is that it can quickly reach a steady state, give quantitative results of working capacity and selectivity, and expose any potential issues without more sophisticated process control. The six steps include adsorption, pressurization, pressure equalization, evacuation, pressure equalization, re-pressurization as indicated in Figure 4. The process was kept running continuously and automatically as long as there is flue gas supply, as the purpose of the project is to investigate the performance with long term running and realistic process conditions. Figure 5 indicates a steady CO_2 product purity over a period of time and the drop indicates the loss of CO_2 flow to the analyzer which would lead to a drop in reading as a characteristic of the instruments when low flow is encountered. Figure 6 shows a temperature swing for several cycles which shows a reasonable working capacity of the adsorbents for both water and CO_2. The temperature swing is an important diagnostic tool in making judgments of working capacity and adsorption front movement. As shown in Figure 7, a stable and symmetric pressure swing was also realized during the run. Adsorption pressure varies from 110 – 140 kPa.a and desorption pressure varies from 2kPa. – 5 kPa.a

After continuous running of the process using a 6-step cycle without purge for a week or so, a purity: ~71% and a recovery of ~60% were achieved. This performance is not optimized performance as the system running was interrupted from time to time. Further optimization and adoption of complex cycle with product purges is expected to yield much higher purity and higher recovery.

2.3. Engineering issues

During the commissioning and operation of the adsorption rig, engineering issues faced were corrosion, ash deposits, water condensation, large void space contamination, equipment faults, etc. Corrosion of the feed blower was experienced during operation. The blower used is aluminum-based rotating blade type blower. This blower was chosen over a stainless steel version due to a significantly lower cost. The blower often jammed when restarting from a prolonged shutdown, apparently by formation of solids in the gap between the edge of rotating blade and internal chamber wall. Analysis of the solids indicates the corrosion of the blower was caused by sulfuric acid carried over from the direct contact cooler and formation of sulphates when the rig was shut down. An air inlet line was installed to purge out the line during shutdown to knock out SOx, NOx and water.

Another important issue identified is water condensation. The feed pipe line is long (3-5 meters) allowing for gas cool down and water condensation. The knock-out (KO) pot was unable to remove the condensate. Therefore, a small water reservoir formed at the bottom of the adsorption column which significantly affected the pumping capacity of the vacuum pumps as additional work must be done to evaporate the water. In addition, during non-evacuation steps, this water will be adsorbed and penetrate the adsorbents which will result in a reduction of working capacity of the CO_2-selective adsorbent and eventual contamination of the adsorbent. Such condensation problems were rectified by increasing the feed gas temperature and installing a drain valve at the bottom of columns. Testing is currently underway with these modifications in place. These problems were largely due to the intermittent operation regime of the trials and would not be expected to be significant issues for a continuously operating plant.

3. Membranes

3.1. Background and Process Description

The membrane rig is considerably smaller than either the solvent or adsorption units (15 tonnes of CO_2/annum). This small scale allows us to test novel membranes developed within the laboratory in addition to small commercial modules. The membrane plant includes an upstream cooler/knockout pot to remove condensable impurities. Two process options are then available. The first process line is used to test polymeric gas separation membranes at ambient temperature. The partial pressure difference across this membrane is maximized through the use of a blower on the feed gas, increasing the flue gas pressure to 145 kPa.a, and a vacuum pump on the permeate side; producing a CO_2 partial pressure driving force of approximately 20 kPa across the membrane. The second process line is used to evaluate membrane gas absorption technology, which is a novel hybrid of solvent and membranes that combine the benefits of both. The use of solvent ensures selective separation of CO_2 from the process gas, through chemical absorption. The membrane contactor provides the necessary gas/liquid contact but ensures that the two phases are not directly mixed, thus overcoming issues such as flooding, foaming and entrainment. The membrane is porous and therefore provides no selectivity itself, but acts only as the transport interface between the solvent and process gas. Of importance in these trials is that membranes will be exposed to the flue gas stream for long periods allowing for extended performance testing.

3.2. Pilot Plant Performance

The membrane gas separation pilot plant has trialled a single pass hollow fibre polysulfone based module, with a laboratory CO_2/N_2 selectivity of 14.3. Currently operation of the membrane module indicates ~25 % of the CO_2 in the feed passes through to the permeate stream. In addition, minor components in the flue gas, NOx and CO have been shown not to pass through the membrane, and are retained with N_2. There is currently not enough information to determine the behaviour of SOx in the membrane gas separation process.

The membrane gas-solvent absorption pilot plant has trialled a hollow fibre polypropylene contactor, where the solvent is drawn directly from the solvent capture plant. The contactor provides ~8 m^2 surface area between the solvent and flue gas, and is designed to handle ~10 kg/hr of solvent. The performance of the contactor with PuraTreat-F (BASF) solvent produced a CO_2 loading into the solvent of 0.13 moles of CO_2 for every mole of PuraTreat-F passing through the plant. This results in 85% of the CO_2 in the flue gas being absorbed, under the current operating conditions. Again, the minor components present in the feed, NOx and CO, remain with the flue gas and do not absorb into the solvent, while for SOx, there is insufficient evidence to determine if it is reacting with the solvent. More recently, the membrane gas-solvent absorption plant has begun operating with potassium carbonate as the solvent, allowing for future comparison of CO_2 capture and efficiency between solvent systems.

4. Conclusions

Confidence in the construction, erection and the successful operation of capture plants as retrofits into an existing power plant setting has been established. Direct application of these three different capture technologies in parallel has been demonstrated. The solvent unit is one of the largest of its kind in power plant applications. Skills development achieved in all areas are also significant. The uniqueness of this project lies in the strong collaboration between researchers from several Universities, the CO2CRC, Process Group and our industry partner International Power. This has allowed the use of expertise across a range of discipline areas. The project has been extended for another nine months which will allow further data collection to prepare a more comprehensive report. One of the main objectives of the study is to confirm, by techno-economic assessment, the best potential capture technique(s) for post-combustion applications. Much of this techno-economic assessment is yet to be completed but will rely heavily upon the experimental data from the plants.

5. Acknowledgements

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